The effect of glass fiber length on compressive and flexural strength of reinforced geopolymer

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Abstract. The use of fly ash in the development of geopolymers is considerably practical in minimizing landfills. In addition, to preserve the environment, this approach may also help converting waste material to profitable returns. Currently, geopolymers are used in numerous applications owing to their properties that are comparable as the conventional material of Ordinary Portland Cement (OPC). A few advantageous properties of the geopolymers included resistant to acid, fast setting, high compressive strength and produce low carbon dioxide gas to the atmosphere. However, chemical interaction of raw aluminosilicates reactive precursor with an aqueous alkaline solution during synthesis process has commonly produced a porous geopolymer, which gives the limitation to the geopolymer performance. This weakness may be recovered by implementing fiber reinforcement to improve the properties and reduce the number of internal pores of the geopolymer. This study evaluates the enhancement recorded in geopolymer properties prior to addition of glass fiber into geopolymer matrix. The results of adhesion, flexural and compressive strength of geopolymer significantly increased by addition of glass fiber.

Introduction

Geopolymers are synthetic green polymeric materials formed by chemical process of high aluminosilicates raw materials such as coal fly ash, granulated blast furnace slag, slag and mineral clays (metakaolin) with any alkaline or alkaline silicate solution with produce final product of solid material. The term “geopolymer” was being introduced by J. Davidovits in 1970s. The term was used as to highlight some of the resemblances of the geopolymers with organic thermoset resins [1]. In 1980-1990, a product known as “pyrament” that having superior strength was introduced and it received interest of the research community as a direction towards the future building material [2].

The history of alkali activation technology was first initiated in 1908. Kuhl et.al [3] revealed their first innovation called —slag cement using alkaline component with blast furnace slag (BFS). In 1930-1950, first lab scale research on cement prepared from steel slag and alkalis were published by Prudon et.al in Belgium [4]. Starting from the date, this material was commercially used and applied in building construction. The development of geopolymer by fly ash based began in 1990s by Wastiels et.al [5] with combination of blast furnace slag. Geopolymers are consisted of three main components; raw aluminosilicates materials as precursor, alkaline activator and water. The geopolymer properties are strongly influenced by the type of precursor used, the alkaline activator type and concentration, the particle size of precursor and the water content.

Chemical interaction of raw aluminosilicates reactive precursor with an aqueous alkaline solution during synthesis process has commonly produced a porous geopolymer. This weakness may be recovered by implementing fiber to improve the strength and reduce the number of internal pores of the geopolymer [6], [7]. Fiber in the forms of long unidirectional, whiskers and particles have been utilized as reinforcement in the geopolymer composites to enhance the properties. A few types of fiber including carbon, basalt and natural whose length was approximate with 14 mm, 16 mm and 30 mm, respectively, were used in existing studies [8], [9].

The positive effects of fiber on hardened mechanical properties of reinforced geopolymer have been the subject of numerous studies focusing on the cracking and toughening mechanisms of the fiber according to their shape, volume fraction, and orientation. Despite the superior mechanical properties, fiber reduce the workability of geopolymer paste, which results in the excessive void formation and poor compaction. Thus, a compromise between hardened behavior and fresh properties is essential for applicability.

As seen in Fig. 1 regardless of the fiber type and geometry, increasing the fiber content reduces the flow ability of fiber-reinforced geopolymer. The reduced workability can be explained as a result of an increase in yield stress of the fresh reinforced geopolymer due to the contact network between rigid fiber inside the matrix, proportionate increased with fiber content, equivalent diameter, and aspect ratio. The critical concentration value was suggested to be in the range of 0.2%–2% for the geopolymer and cementitious composites [10]. When the fiber content increases over a critical concentration, the fiber tend to get uneven dispersion and form clumps or balls, and even very valuable matrices might not pass through the congested fiber network properly. Therefore, the fresh matrix requires more vibration to lose its harsh static mode and form the mold [11].

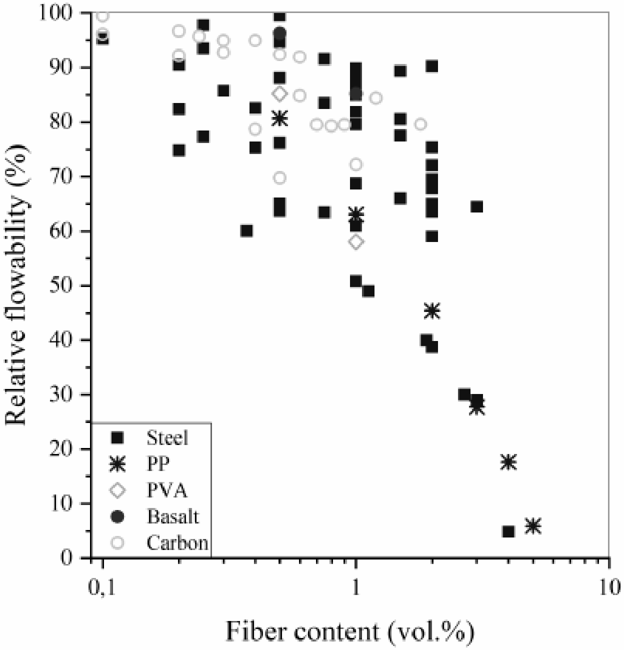

Fig 1: Relative flow ability of fiber reinforced geopolymer composites compared with plain matrices. Adapted from Ref [12]

Drying shrinkage of geopolymers is due to the high capillary pressure produced between wet and dry zones of the micropore network, which leads to specimen deformation and crack initiation. To control the drying shrinkage, two approaches have been often followed: (1) the modification of the pore structure to minimize capillary porosity and to control water loss during curing and (2) the inclusion of inert or reactive fillers and fiber [13]. Several studies have indicated that fiber content, fiber modulus, and fiber-binder interaction are the dominant factors in controlling the shrinkage of reinforced geopolymer composites [14]. Fig. 2 shows the influence of two fiber on controlling the shrinkage of fly ash-based geopolymer. The incorporation of PP and steel fiber even in small amount, 0.5 vol%, reduced the drying shrinkage of the composite specimens significantly. Increasing the steel fiber content to 2 vol% and above resulted in almost no shrinkage. While, the similar reduction was not observed for the same content of PP fiber, and even it showed an adverse effect when fiber content was increased to 4 vol%. This can be ascribed to the poor compaction of the geopolymer lower stiffness of the PP fiber integrated with weak fiber-binder interaction is other reasons for poor performance of the PP fiber compared to the steel fiber. Similar superior shrinkage performance was observed for PVA fiber-reinforced geopolymers as compared with PP fiber due to the hydrophilic nature and higher stiffness of PVA fiber [15]. Besides, it was reported that using a longer fiber can (1) reduce, (2) increase, or not change the shrinkage of geopolymer composites. Furthermore, the shrinkage trend of fiber- reinforced geopolymer composites is affected by the nature of the binder and curing conditions. For example, for the same type and amount of fiber, the shrinkage of slag- based geopolymer composite was reduced by variation of environmental humidity ranging from 50% to 95%, while fly ash-based geopolymer composite was less sensitive to environmental humidity.

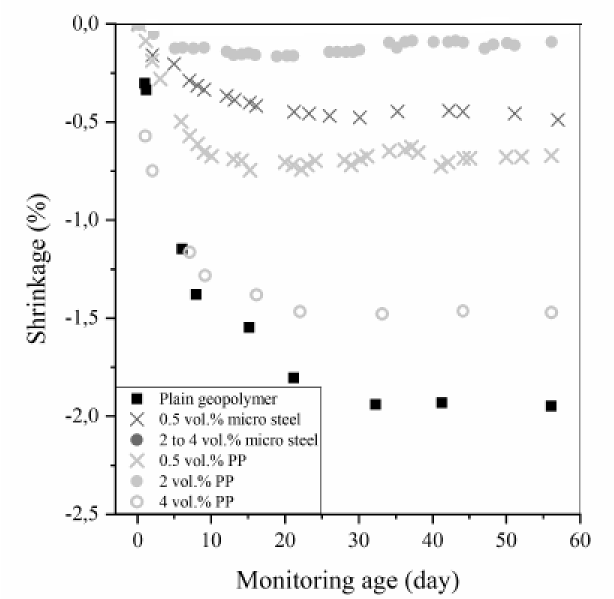

Fig 2: Drying shrinkage of steel and polypropylene fiber reinforced geopolymer. Adapted from Ref [12]

Previous studies by PVA and alumina fiber have shown that as fiber diameter increases, it reduces mechanical properties as well as fiber modulus fiber [16], [17]. This is because fiber imperfections increase when the diameter of the fiber is large compared to the smaller diameter. The fiber aspect ratio denotes the ratio of fiber length to its diameter. The growing interest to add fiber in the fabrication of geopolymer composite make it very important to comprehensively evaluate the properties of that composite via the addition of fiber in the system. Researchers focus on the effect of fiber volume fraction and how this volume does significantly affect the distribution of fiber within the matrix, which indirectly influenced the positioning behavior of fiber and matrix. This part is very crucial to understand as to answer the trend of stress being transferred with the composite. Not only to that aspect, the mechanical properties of geopolymer composite also affected by the fiber aspect ratio.

Shouha et al. [18] observed the effect of fiber aspect ratio in the geopolymer composite reinforced with carbon. The tensile property of geopolymer composite was evaluated. It was found that tensile strength improved until the fiber aspect ratio increases up to 20. Further increasing the ratio, gives nothing enhancement to the composite properties. A similar finding was also supported by Lin et al. [19] in his studies using sheet like short carbon fiber. They found that length of fiber was significantly affected to the tensile strength of composite. However, contracts finding on the effect of fiber aspect ratio on the composite properties were found by several studies. Sudhikumar et al. observed the effect of 25, 38 and 50 fiber aspect ratios on the strength properties of fibrous ferrocement geopolymer composite. Higher compressive strength and flexural strength were recorded at 25 MPa and 38 MPa. But, by increasing the ratio to 50, yield lower strength of composite. They claimed that at lower fiber aspect ratio, more adsorption of stress by composite. The results have been shown with lower aspect ratio, give higher compressive and flexural strength. Study by Jose et al. [20] has successfully developed a reinforced composite by Prosopis juliflora with multiple fiber aspect ratio with fiber length from 46 to 227 mm and fiber loadings from 5 to 32 wt% was evaluated. The study found that the optimum fiber aspect ratio and fiber loading was at 136 and 23.53 wt% for obtaining the composite with high strength. On top of that, there was a limited study explored where the potential of short fibers, especially a glass fiber in the development of reinforced geopolymer. Short glass fiber may offer more advantages over the other kinds of fiber due to their isotropic mechanical behavior, abundantly available in the market and more cost effectively. Thus, the development of the short glass fiber reinforced geopolymer is needed to be explored so that a new outcome from the study may provide beneficial knowledge to community.

Research Methodology

Materials

Raw materials used in the present research including coal fly ash, sodium hydroxide (NaOH), and glass fiber. Coal fly ash was procured from a local Malaysia power plant. To minimize the variation in the particle size distribution, and to separate larger particles, the fly ash was sieved using a 45µm sieve through a vibratory sieve shaker (AS200 Basic RETSCH, Germany). Chemical composition, the presence of different phases and particle size analysis of the fly ash was characterized prior to its use as geopolymer. Sodium hydroxide (99%) was procured from Merck Millipore, Subang, Malaysia. Standard solution of the required concentrations of this base was prepared using distilled water. The synthesis of geopolymer consisted of three steps; (i) preparation of the alkali activator solution, (ii) mixing of alkali activator with fly ash and (iii) curing of geopolymer. Prior to the development of geopolymer the ratio of Na: Al ratio, water: solid ratio and curing days was fixed at 1.0, 0.33 and 3 days, respectively. The glass fiber chopped strands were imported from JN Technologies PvT. Ltd Glass strands were mainly composed of silicon oxide (SiO_2), alumina oxide (Al_2O_3), calcium oxide (CaO), manganese oxide (MnO), sulfur trioxide (SO_3), magnesium oxide (MgO), sodium oxide (Na_2O), ferum oxide (Fe_2O_3), potassium oxide (K_2O), titanium oxide (TiO_2) and phosphorus oxide (P_2O_5). The average diameter of the glass fiber was 14 µm with two different lengths of 6 mm and 12mm. The fiber was incorporated in the geopolymer matrix using an ultrasonic bath sonicator for 10-minute agitation process. This approach was to ensure the glass fiber was well mixed and homogeneous composite was formed. Subsequently, the homogeneity of the composite was reconfirmed by a field emission scanning electron microscope (FESEM). The content of fiber varied from 0.2 -2.0 wt%. Table 1 shows the test matrix used in incorporating the fiber into geopolymer system.

Table 1: Fiber length and fiber weight in incorporating system

Fiber length	wt%									
6 mm	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2
12 mm	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2

Results and Discussions

Diffractometry Analysis of Fly Ash

X-rays diffraction (XRD) analysis was conducted to investigate the qualitative and quantitative analysis of the various phases existing in the ashes. The XRD analysis of the fly ash was shown in Fig. 3. As can be seen, the ash composed of crystalline and amorphous phases. The sharp and visible peaks were representing crystalline phase, whereas the hump from the baseline in the 2-theta range of 18- 40° signified a presence of amorphous materials. The crystalline phase of quartz was detected at 20.91°, 25.45°, 26.52°, 43.26°, 50.29° and 68.37°. The result was found consistent with the pattern of quartzite, ICOD card no. 01-085-0457.

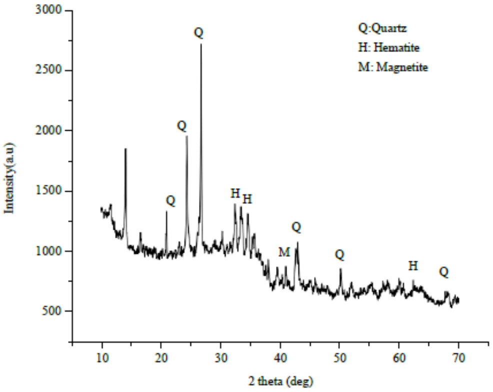

Fig 3: X-rays diffraction analysis of the raw materials of fly ash

Microstructural Image of Geopolymer

Microstructural analysis provides information about the microstructure of materials. Fig. 4 (a) and (b) shows FESEM images of unreinforced and reinforced geopolymers, respectively. Porous internal structure of geopolymer with some unreacted fly ash could be observed in Fig. 4 (a). Apparently, the presence of glass fiber into geopolymer, led to reduce the number of pores inside the system. The fiber significantly closed the pores via bridging effect between fiber surface and geopolymer paste. The fiber was also seemed to dispersed uniformly and well scattered in the paste.

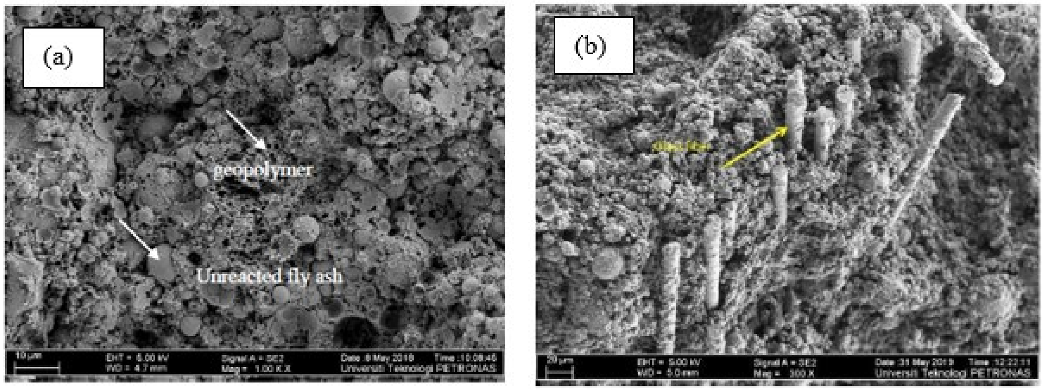

Fig. 4: FESEM image of (a) unreinforced geopolymer; (b) glass fiber reinforced geopolymer

Adhesion strength

The pull-out tests were carried out to analyze the adhesion strength of the reinforced geopolymer to the steel plate. The adhesion test was determined using Elcometer 108, according to ASTM D-

4541 [21]. Fig. 5 shows the adhesion strength of the reinforced geopolymer that was cured isothermally at 60 °C for three days. The adhesion strength showed variations with mixed design.

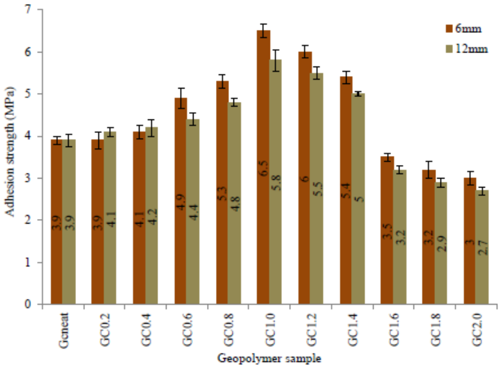

Fig. 5: Adhesion strength of 6mm and 12mm glass fiber reinforced geopolymer at three days curing time

The strength of reinforced geopolymer for both 6 mm and 12 mm was increased with increasing content of fiber up to 1.0 wt%, in with the highest strength of 6.5 MPa for 6 mm and 5.8 MPa for 12 mm fiber. This could be explained by FESEM image shown in Fig 4 (b). The fiber was adhered strongly with the paste, consequently produced geopolymer with compact structure, led to better strengths. However, when the fiber content was further from 1.0 wt% to 2.0 wt%, the strength decreased gradually. The lowest strength of 3.0 MPa and 2.7 MPa was obtained for 6 mm and 12 mm fiber, respectively. This finding was comparable to a study reported by Zhao et al. [22] and Herrera et al. [23].

Flexural strength

Effect of glass fiber content on the flexural strength of the samples was discussed. Fig. 6 presented the flexural strength of the geopolymer sample.

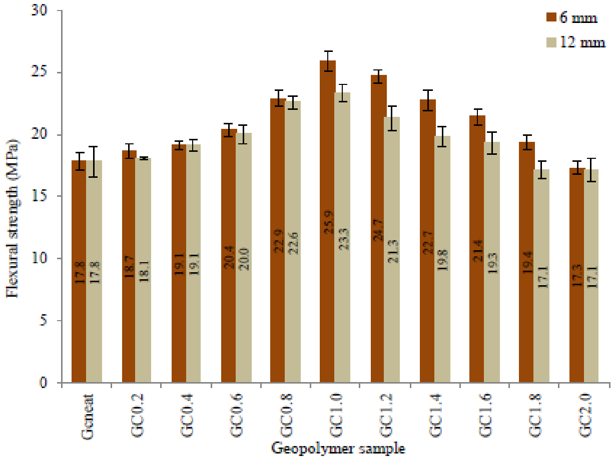

Fig. 6: Flexural strength of 6mm and 12mm glass fiber reinforced geopolymer at three days curing time

Based on the Fig. 6, the reinforced geopolymer confirmed the high-quality advancement in the aspect of flexural strength. The higher the fiber content, the higher the bending strength compared to the neat geopolymer (unreinforced geopolymer). It can be seen, only 17.8 MPa of strength was recorded for unreinforced geopolymer. Meanwhile, the flexural strength of 6 mm reinforced geopolymer glass fiber increased drastically with 0.2 wt% up to 1.0 wt% of glass fiber. Interestingly, the flexural strength decreased with further increase in fiber content up to 2%. A similar trend was also observed by adding 12 mm glass fiber into the matrix. However, the increment of the flexural strength was not as high as the geopolymer that was reinforced with 6 mm length fiber. It was expected with too low and high fiber contents at 0.2 and 2.0 wt%, causes high distribution density of small cracks formed in geopolymer which could consume a lot of energy, consequently lead to low strength in the flexural test [24].

Compressive Strength

Compression test of glass fiber reinforced geopolymer was carried out by Liangdong compression testing machine. Fig. 7 (a) and (b) presents the compressive strength of 6 mm and 12 mm glass fiber reinforced geopolymer, respectively.

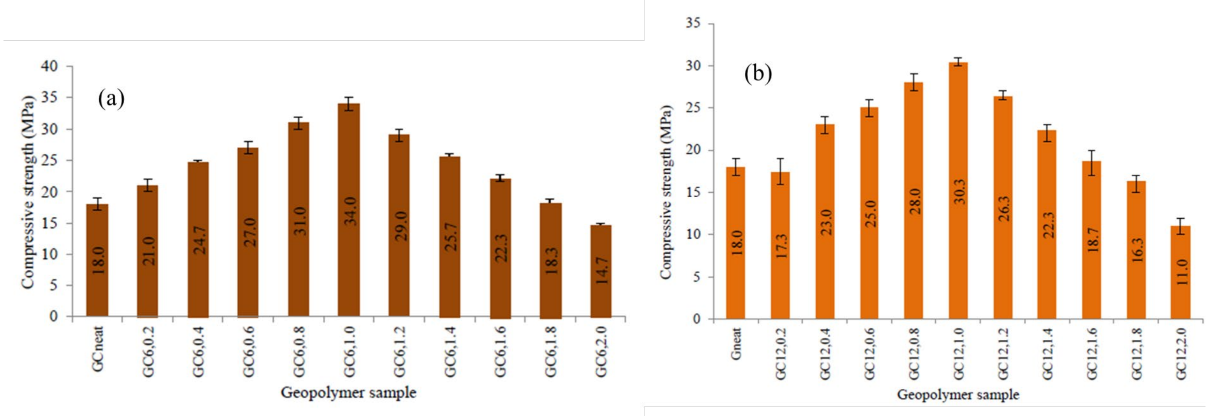

Fig. 7: Compressive strength of (a) 6mm glass fiber reinforced geopolymer; (b) 12mm glass fiber reinforced geopolymer

The addition of different concentrations of glass fiber into geopolymer affected the compressive strength. The addition of the glass fiber led to an improvement of the compressive strength of both 6 mm and 12 mm fiber length systems. The highest compressive strength in the geopolymer was achieved with the addition of 1 wt% of 6 mm length glass fiber at 89% greater neat geopolymer. In 12 mm system, the geopolymer was only managed to record 69% strength increment compared to the neat geopolymer. Noticeably, the highest strength obtained for 6 mm and 12 mm system was 34MPa and 30 MPA, respectively.

Three mechanisms can be related to the enhancement in compressive strength; firstly, the bridging effect of fiber on the pores (shown in Fig. 8), produced a compact and dense geopolymer structure. Secondly, the potential of the fiber to delay a propagation of micro crack, thus indirectly improved the energy absorption and ductility of the composite through a bridging effect, leading to a greater load carrying capacity. Thirdly, the well dispersion of the fiber in geopolymer matrix significantly created a strong bonding at the fiber / matrix interface. The optimal transferring of stress from matrix to fiber might occur by having a good interface interaction, thus significantly improve the compressive strength of composites [14 - 16].

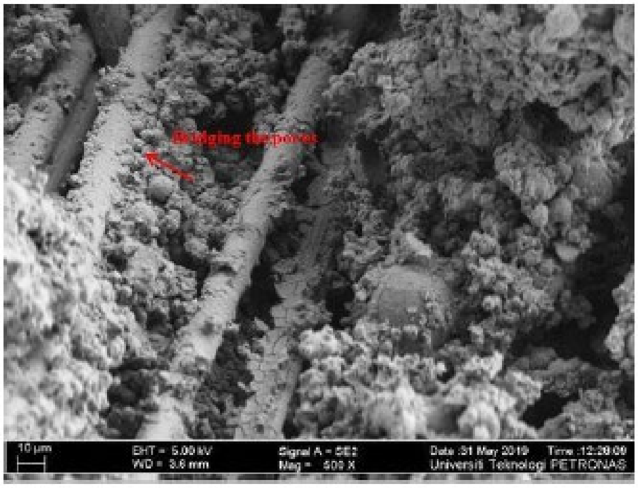

Fig. 8: Bridging effect of fiber into pores

Summary

In present research work, a reinforced geopolymer with short glass fiber was successfully developed and studied for its mechanical properties, i.e. adhesion, flexural and compressive strength. Fly ash was used as a precursor in geopolymer development. Two fiber length of 6 mm and 12 mm was chosen to understand the influence of length to the geopolymer properties. It was noticed the incorporation of fiber into geopolymer managed to enhance the flexural and compressive strength of geopolymer. The present work proven that 6mm fiber length gives better strength to the geopolymer. It was also noticed further increased fiber content 1 wt% onwards, resulted to poor strength of geopolymer.

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